# Transient hydrogeological behaviour of the LTA cover with capillary barrier effects

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ABSTRACT
A cover with capillary barrier effects (CCBE) made of three layers was constructed on the LTA tailings impoundment to control acid mine drainage (AMD) production. This cover was designed to act as an oxygen barrier. Monitoring results collected four times per year since 1996, showed that the CCBE generally meets, and even exceeds, the design objectives in term of oxygen flux. To better assess the performance of the CCBE, intensive (daily) measurements were recently performed at two strategic locations (on the flat and on the sloping area). These measurements show the role of the rainfall intensity on the recharge of the CCBE. Results also indicate that the *in situ* water retention curve of the moisture-retaining layer shows hysteresis effects. Finally, measurements during wintertime confirm the presence of freezing conditions in the cover, especially in the flat area.

RÉSUMÉ
Une couverture avec effets de barrière capillaire (CEBC) a été construite sur le parc à résidus LTA en vue de limiter la production de drainage minier acide (DMA). Cette couverture agit comme une barrière à la migration d'oxygène. Les résultats de mesures prises quatre fois par année depuis 1996, ont montré que la CEBC a atteint et même dépasse les objectifs initiaux de design en terme de flux d'oxygène. Afin de mieux évaluer la performance de la CEBC, des mesures intensives (une fois par jour) de teneur en eau volumique et de succion ont été effectuées récemment à deux endroits stratégiques (sur le dessus et sur une portion inclinée). Les résultats de ces mesures montrent le rôle de l'intensité des précipitations sur la recharge de la CEBC. Ils montrent également que la courbe de rétention d'eau *in situ* présente des effets d'hystérésis. Enfin, les mesures réalisées en hiver confirment la présence de conditions de gel dans le recouvrement, particulièrement sur la portion plate du parc.

## 1 INTRODUCTION

The LTA site is located in the Abitibi region, in the province of Québec, Canada. The climate of this region is classified as moderate continental, and is characterized by contrasted seasons: winter is cold; spring and fall are relatively wet with low evaporation rate; and summer is relatively hot and dry. The mean annual temperature is about 1.1°C, the average annual precipitation is 914 mm, and annual evaporation is estimated at 380 mm (Ricard et al. 1997)

Following the mill permanent closure in the fall of 1994, the LTA site was rehabilitated using a cover with capillary barrier effects (CCBE). The objective is to maintain one of its layers at a degree of saturation $S_r$ equal or greater than approximately 85% to control oxidation of sulphide minerals. More details on the site prior to its rehabilitation can be found in McMullen et al. (1997).

The three-layer CCBE (see Figure 1) constructed on the LTA sulphide tailings consists of (from the bottom to top; Ricard et al. 1997):

- A 0.5 m layer of sand used as support and capillary break layer;
- A moisture-retaining layer (MRL) with a thickness of 0.8 m. This layer is made of non acid-generating tailings (called MRN) taken from the nearby Malartic Goldfield property (a site that belongs to the Quebec Natural Resources Ministry- MRN);
- A 0.3 m of sand and gravel placed on the top which serves as drainage and protective layer against evaporation, erosion, and bio-intrusion.

The MRN tailings have a grain-size distribution typical of hard rock tailings (e.g Vick 1990; Aubertin et al. 1996, 2002), with a percentage passing 80 µm between 56 and 88.5 %, a $D_{10}$ [L] (diameter of particles at 10 % passing) between 3 and 7.5 µm, and a uniformity coefficient $C_U$ [-] ($D_{60}/D_{10}$) between 11 and 12.5. The average porosity $n$ [-] of the compacted moisture-retaining layer (MRN tailings) measured in the field is approximately 0.44, with values ranging between 0.36 and 0.49. The bottom sand layer material has a low percentage of fine particles (less than 5 % smaller than 80 µm) and cobbles (no particles with a diameter greater than 15 cm). The *in situ* porosity of the sand upon compaction was between 0.34 and 0.38.

Water retention tests were performed according to ASTM D3152-72 standard. The Air Entry Value [L] ($\psi_a$)

measured in the lab on MRN tailings samples is between 136 to 280 cm of water (or about 13.5 and 28 kPa), depending on their grain-size distribution and porosity.

The saturated hydraulic conductivity $k_{sat}$ [$LT^{-1}$] of MRN tailings, evaluated in rigid wall permeameters (ASTM D5084-90) for a range of porosity *n* between 0.42 and 0.51, varied between $3x10^{-5}$ and $1.9x10^{-4}$ cm/s. The saturated hydraulic conductivity of the sand at *in situ* porosities is between $8\ x10^{-2}$ and $1x10^{-1}$ cm/s, while its $\psi_a$ measured in the lab is between 20 and 40 cm of water. More information on materials properties can be found in Ricard et al. (1997) and Bussière et al. (2003, 2006).

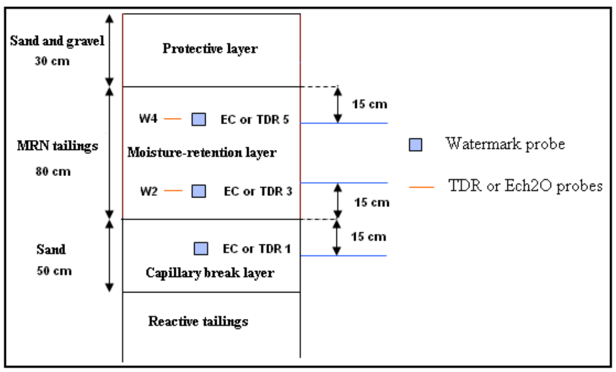


Figure 1: The CCBE Configuration at the LTA site with probes location in the cover layers

The main parameters that have been monitored to evaluate the performance of the LTA cover are the volumetric water content ($\theta$) and suction ($\psi$). These two parameters provide insight on the hydraulic response, which then allows estimating the oxygen flux through the CCBE (e.g. Aubertin et al. 1999; Mbonimpa et al. 2003; Bussière et al. 2003). TDR probes and Watermark sensors were first used (in 1996; see stations CS 96- and PS 96- in Figure 2) to monitor the *in situ* volumetric water content and suction in the various layers of the CCBE (e.g. Ricard et al. 1999; Golder Associates 1996, 1999). In 2006 (see stations CS 06- and PS 06- in Figure 2), a new series of monitoring stations were installed to update cover instrumentation. Overall, more than 50 stations are installed to evaluate the *in situ* performance of the cover. It is also worth mentioning that oxygen consumption tests and piezometric measurements have been also used to assess the response of the CCBE (not discussed here).

The main results obtained during the first nine years of monitoring at the LTA site (Bussière et al. 2003, 2006; Maqsoud et al. 2005) show that capillary barrier effects are well developed (where required) between the different cover layers. For the flat area and at the bottom of sloping areas, $\theta$ in the moisture-retaining layer exceed the design criteria of 0.37 (corresponding to an effective diffusion coefficient $D_e$ less than $10^{-8}$ m²/s; see McMullen et al. 1997 for more information) and the $\psi$ values remains below the air entry value of the moisture-retaining material. For inclined areas (representing approximately 5% of the impoundment surface), a slope effect is observed, which tends to desaturate the moisture-retaining layer especially during prolonged dry periods. In these inclined zones, the design criteria can be temporarily exceeded (i.e. $S_r$<85%) near the top of the slope. The cover overall performance meets the original objectives despite occasional and localized increase in oxygen flux.

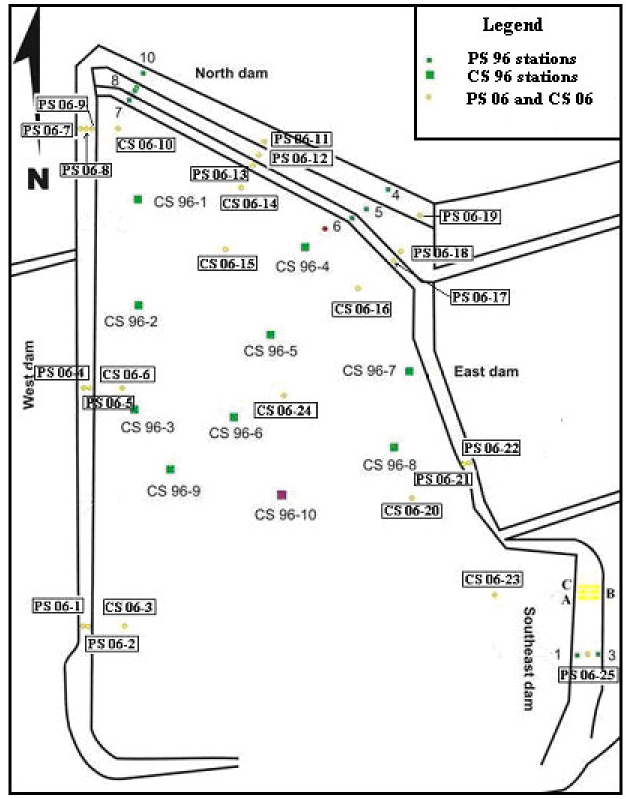


Figure 2: Monitoring station Locations

The assessment of the LTA cover performance was based mainly on occasional measurements during the summer (typically 4 to 8 measurements per year; see Bussière et al. 2006). These measurements give the main trends, but do not provide much information on the short-term variations. Daily measurements of $\theta$ and $\psi$ were proposed to improve our understanding of the LTA CCBE transient hydraulic behaviour. Hence, two new monitoring stations were installed at two strategic locations (one on the flat and one on the sloping portion), and followed for a one year period. The main results obtained are presented in the following.

## 2 NEW MONITORING STATIONS

The first monitoring stations is located on the flat area called (CS 06-10) and the second one (PS 06-25) is located near the mid-height of the south-east dyke (see Figure 2 for location). Measurements of volumetric water content and suction at these two stations were performed using $Ech_2O$ probes and Watermark sensors respectively.

### 2.1 Volumetric water content measurements

The $Ech_2O$ probes use the Frequency Domain (FD) technique to estimate the volumetric water content of a soil. The electrical capacitance of a condenser, which uses the soil as dielectric depends on the water content in this media. By connecting this condenser to an oscillator to form an electric circuit, the changes in the volumetric water content in the media can be detected from the frequency variations of the circuit. The soil permittivity (directly related to the volumetric water content) is given by measuring the period of charge of the capacitor created by the ground conditions.

The FD technique was identified by Wyman (1930), but it was not applied until the development of a probe for *in situ* measurements by Malicki (1983). Thereafter, its use has spread especially with the development of a portable instrument (Dean et al. 1987), which was evaluated by Bell et al. (1987). Other FD probes, having the same design as that of the Time Domain refloctometry (TDR) probes were developed (Robinson and Dean 1993; Hilhorst and Dirksen 1994).

The main advantages of the $Ech_2O$ probes are (Maqsoud et al. 2007): precision of about 0.01 (on the volumetric water content) after calibration, possible measurements in grounds with strong salinity, better resolution than the TDR probes, possibility of connecting the probes to conventional recorders, relatively inexpensive (in comparison with the TDR technology). However some disadvantages were reported such as small volume of influence (diameter approximately 4 cm), impact of local soil density, clay content and air trapping, and the need to define a calibration curve for each tested type of material.

### 2.2 Suction measurements

Watermark sensors were inserted in the moisture-retaining layer for matric suction measurements. These sensors (granular matrix sensor) are made with an electrical resistance, read by a hand-held meter which converts the electric reading to a calibrated suction. The main advantages of this sensor include: no need for periodic maintenance; not subjected to damage by freezing temperatures; the matrix does not dissolve in water (unlike gypsum block). The Watermark sensor gives reliable results typically for suction between 20 to 800 cm of water (2 to 80 kPa) (e.g. Shock et *al.*, 1999, 2002; Aubertin et *al.*, 2002). However, the sensor is known to be influenced by water salinity; this is not a concern in this study since the sensors are installed in the cover above the acid-generating tailings.

### 2.3 Configuration of the monitoring stations

Each station (CS 06-10 and PS 06-25) is equipped with three $Ech_2O$ probes (EC1, EC3 and EC5) for volumetric water content measurements and two Watermark probes (W2 and W4) for suction measurements. EC1 probes are located in the capillary break layer (sand layer at the base of the CCBE) at 15 cm from the interface between the sand and the moisture-retaining layer (see Figure 1 for locations). EC3 probes are placed at 15 cm from the base of the moisture-retaining layer, while EC5 probes are located in this same layer at 15 cm from the interface with the top sand layer. Watermark sensors W2 are located at the same elevation as the EC3 probes, while Watermark sensors W4 are placed at the same elevation as EC5 probes. The $Ech_2O$ and Watermark probes are connected to data loggers for regular measurements. Suction ($\psi$) measurements were only performed on the flat area and in the moisture-retaining layer.

### 2.4 Calibration of $Ech_2O$ probes

As mentioned previously, a calibration curve is needed for each material monitored with $Ech_2O$ probes. Therefore, the cover materials were sampled at PS 06-25 and CS 06-10 stations. These materials were placed in containers at different known density and gravimetric water content. Measurements from the $Ech_2O$ probes were compared with volumetric water contents. Results used for the probes calibration are presented in Figure 3 and 4.

Two calibration curves were obtained for the two materials samples from the moisture-retaining layer at the two monitoring stations (Station CS 06-10 and Station PS 06-24). The objective was to evaluate if both materials had the same calibration curves. Figure 3 shows that the coefficient of correlation between the output signal and the volumetric water content are greater than 0.99 for both locations and that the regression equations are nearly identical confirming that the two materials can be considered as identical.

For the sandy material, acting as capillary break layer, a single calibration curve was determined (the sand comes from only one pit. Again, the relationship obtained is linear (see Figure 4) but the coefficient of correlation is lower (approximately 0.90) than for the moisture-retaining layer tailings. This difference could be due (at least in part) to difficulties in maintaining a constant and uniform water content in the sand during the calibration test and to the precision of the data and readings themselves.

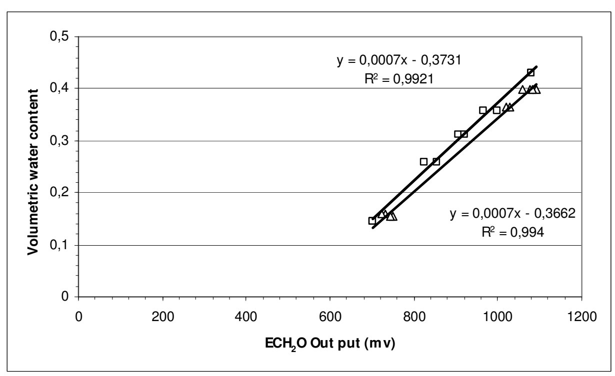


Figure 3: $Ech_2O$ calibration using the MRN tailings at the two probes locations

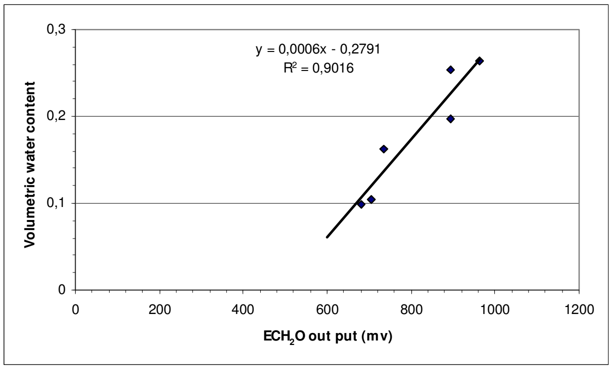


Figure 4: $Ech_2O$ calibration using the sandy material

The equations presented in Figures 3 and 4 have been to convert probe readings measurements (output signal) into volumetric water content values.

## 3 MAIN RESULTS

Measured values of the volumetric water content and suction at stations CS 06-10 and PS 06-25 in 2006 and 2007 are presented in the following paragraphs.

### 3.1 Volumetric water content measurements

Regular (daily) measurements at Station CS 06-10 (flat area) and Station PS 06-24 (sloping area) were performed from June 30 2006 to May 30 2007. The results are divided in two parts: the first one goes from 30 June to October 31 and the second one from November 1st to 30 May (which includes the winter period).

#### 3.1.1 Flat surface (CS 06-10)

Measurements results performed at station CS 06-10 are presented in Figures 5 and 6 for the first and second period respectively.

Figure 5 shows the volumetric water content values measured in the capillary break layer (EC1 - sandy layer) and near the bottom (EC 3) and top (EC 5) of the moisture-retaining layer. This figure also presents precipitation measurements at the weather station of Val-Or (located at approximately 25 km from the LTA site). One can see that the volumetric water contents in the moisture-retaining layer are much larger than in the capillary break layer. The $\theta$ value in the moisture-retaining layer stayed above 0.34 during the entire period (from June to October). The $\theta$ values in capillary break layer stayed close to 0.10 during the same period. The contrast between these values reflects the presence of capillary barrier effects. Moreover, it is observed that the water content near the bottom of the moisture-retaining layer is generally higher than near the top of this layer, but the difference is only of about 2 %. As it will be shown below, this behaviour is mainly due to a slightly larger suction at higher elevation from the interface between the capillary break layer and the moisture-retaining layer.

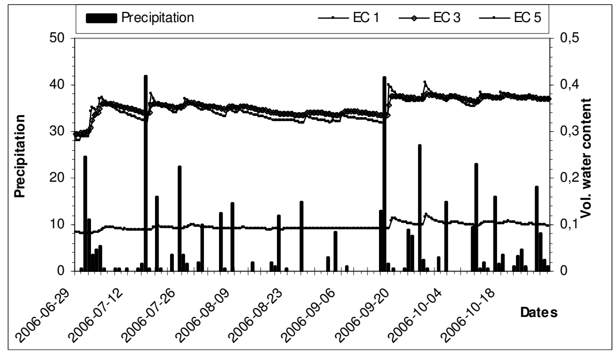


Figure 5: Measured values of the volumetric water content at station CS 06-10 (flat area): from June 30 to October 31

During the measurement period, the CCBE was subjected to different wetting and drying events. As shown in Figure 5, the measured cycles are directly related to these events. The magnitude of the volumetric water content increases is directly related to the intensity and duration of the precipitation. For example, two relatively large precipitation events (greater than 40 mm over 24 hours) were observed on July 15 and September 10. These events were followed, over two days, by an increase of 2 to 5 % of the volumetric water content in the moisture-retaining layer.

Fluctuations of θ values in the capillary break layer are typically less pronounced than in the moisture-retaining layer. The value of θ varied between 0.08 and 0.10 for the entire measurement period. Hence, the impact of the precipitation events on the volumetric water content is low.

Results for the second monitored period, from November 1st 2006 to May 30 2007, are presented in Figure 6. Before January 2007, the hydrogeological behaviour is relatively similar to the one observed during the first measurement period. Capillary barrier effects remains well developed, with low volumetric water contents ($\theta \simeq 0.10$) in the capillary break layer and higher volumetric water contents in the moisture retaining layer (between 0.36 and 0.40).

During the winter and early spring, there were significant differences in terms of volumetric water content. Between January and May 2007, a significant decrease of the volumetric water content near the top and near the bottom of the moisture-retaining layer was registered; the decrease in the $\theta$ value was more important near the top of the moisture retaining layer (see Figure 6) with values dropping from 0.36 to 0.10, compared to values remaining above 0.24 near the base of the moisture-retaining layer. This behaviour is related to the freezing of water that reduces the amount of moisture that contributes to the probe reading. A slight decrease of the $\theta$ value, of approximately 0.02, was observed for the capillary break layer during the winter period, showing that the capillary break layer, located 1.1 m below the surface, was less significantly affected by freezing at the CS 06-10 monitoring station.

During the snow melt, in April-May 2007, the volumetric water content in the moisture-retaining layer increased to values close to those observed before the freezing period, and even greater near the top (i.e. $\theta$ = 0.44) which corresponds to complete saturation. At that time the $\theta$ values near the top of the layer approach those measured near the base of the moisture-retaining layer ($\theta$ = 0.36-0.38) following melting of snow and ice. The melting process does not seem to affect significantly the volumetric water content in the capillary break layer, which only increases to approximately 0.12 for a few days, and then rapidly comes back to about 0.10.

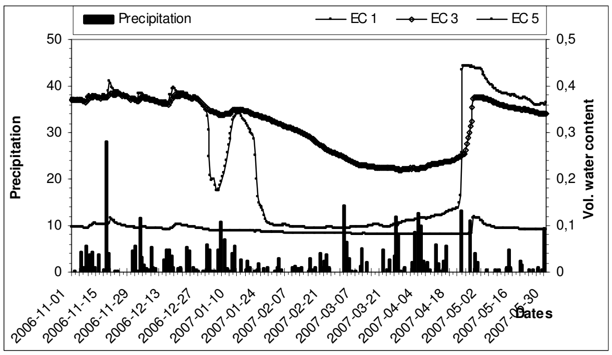


Figure 6: Measured values of the volumetric water content at station CS 06-10, from November 1st to 30 May 2007

3.1.2 Sloping area (PS 06-25)

Measurements performed at mid-height of the south-east dike, at station PS 06-25, are presented in Figures 7 and 8 for the first and the second monitoring period, respectively.

From 30 June to October 31, the hydrogeological behaviour is relatively similar to the one observed on the flat area, with $\theta$ values in the moisture-retaining layer being higher than in the capillary break layer, confirming the presence of capillary barrier effects. However, the absolute $\theta$ values are somewhat different. The difference between the $\theta$ values measured near the top and near the base of the moisture-retaining layer is larger (compared to the flat area); this difference is generally between 0.02 and 0.06 during the summer time, and it can even exceed 0.08. The difference in $\theta$ values between the top and the base of the layer is usually less pronounced during wet periods, following precipitation events (the difference is then between 0.02 and 0.04). Results also show that, during the summer period, the $\theta$ values in the moisture-retaining layer decrease down to 0.24 and 0.30 for the sensors located near the top and the base of the layer respectively. These lower values of volumetric water content are due to the sloping effect, which tends to desaturate the moisture-retaining layer uphill (see Bussière et al. 2003, 2006; Maqsoud et al. 2005).

During the measurement period, there was a succession of wetting and drying events. These cycles are related to the precipitation events, and directly affect the volumetric water content which tends to increase with the intensity of rain.

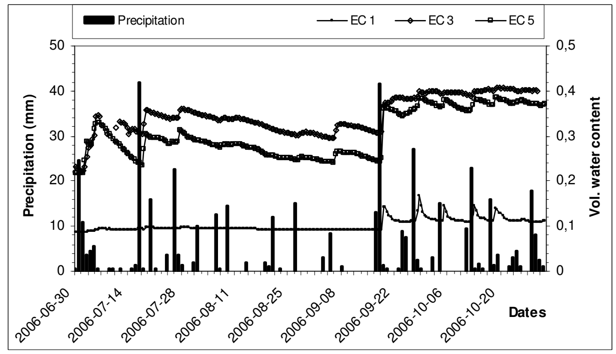


Figure 7: Measured values of volumetric water content at station PS 06-25 (inclined portion of the CCBE), from 30 June to October 31 2006

The variation in the volumetric water content in the capillary break layer is more pronounced for the sloping area of the cover than for the flat area, with values ranging between 0.10 and 0.18. This behaviour is mainly due to the inclination of the cover in the slope that diverts a portion of the water. At a given point, known as the DDL point (e.g. Ross 1990, Aubertin et al. 2009), the water starts to infiltrate the capillary break layer, causing an increased of the $\theta$ value. It is interesting to note that the $\theta$ increase in the capillary break layer tend to occur when the moisture-retaining layer shows $\theta$ values greater than 0.36 (during the fall 2006). When $\theta$ is less than 0.36, the volumetric water content in the capillary break layer remains nearly constant at 0.10. A value of $\theta \approx 0.36$ is deemed to correspond to a suction that is close the water entry value for the sand layer ($\psi \approx 30$ kPa).

Figure 8 shows that results are relatively similar for the period of November 1st to May 30, compared to those measured during the first period at the same location.

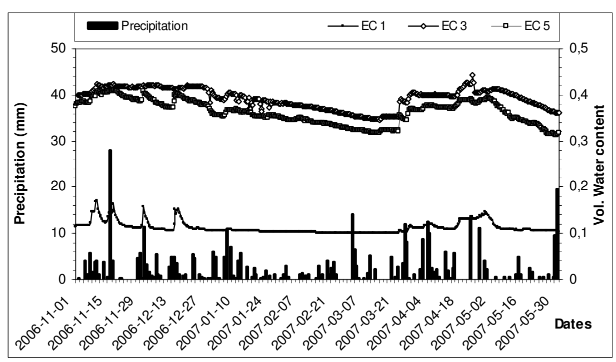


Figure 8: Measured values of the volumetric water content at Station PS 06-25 (inclined portion of the CCBE), from November 1st to 30 May 2007

For instance, $\theta$ values in the moisture-retaining layer vary between 0.32 and 0.42, while those in the capillary break layer are between 0.10 and 0.18. However, the freeze effect observed for the flat area is not as clear for the sloping section as seen by comparing Figure 6 and 8. This difference is mainly attributed to the accumulation of snow (by wind effect - unpublished field observation) in this portion of the site, which reduces the propagation of the cold front downward.

### 3.2 Suction measurements

Suction ($\psi$) measurements were performed on the flat area and in the moisture-retaining layer. Results are presented in Figures 9 and 10. The $\psi$ values measured are in accordance with those of the volumetric water contents (see Figures 5 and 6). When suction increases at values greater than about 20 kPa (which corresponds to approximately the air entry value of the MRL material; see Bussière et al. 2006), the volumetric water content tends to decrease. The suction usually remains below 20 kPa near the base of the moisture-retaining layer, which explains the high volumetric water content. The difference in suction values between the sensors located near the top and near the base of the moisture retaining layer is about 6 kPa. This difference is mainly attributed to the 50 cm difference in elevation of the Watermark probes.

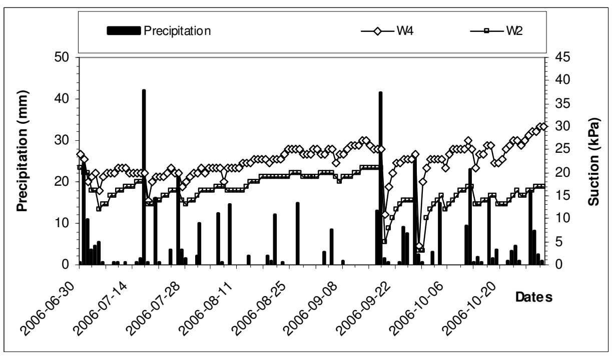


Figure 9: Matric suction measurements on the flat area from 30 June to October 31 2006

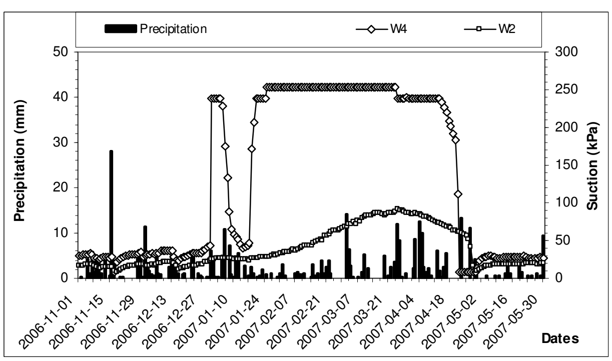


Figure 10: Matric suction measurements on the flat area: from November 1st to 30 May 2007

This difference becomes larger during the winter period (see Figure 10) because the top of the moisture-retaining layer is more affected by freezing.

The declining temperature tends to increase suction (a phenomenon known as cryosuction) particularly near the freezing font. When the water in the sensor is all frozen, the readings reach the maximum value (250 kPa). This value is not necessary a real suction value.

## 4 DISCUSSION

Daily measurements at the station CS 06-10 for suction and volumetric water content are used to obtain the *in situ* water retention curve (WRC). Figure 11 shows the corresponding $\theta$-$\psi$ data. This figure indicates that a unique water retention curve does not describe the behaviour of the *in situ* material. One of the reasons is that the measurements were made during wetting and drying processes, which produce hysteresis effects (e.g. Maqsoud et al. 2002, 2004, 2006).

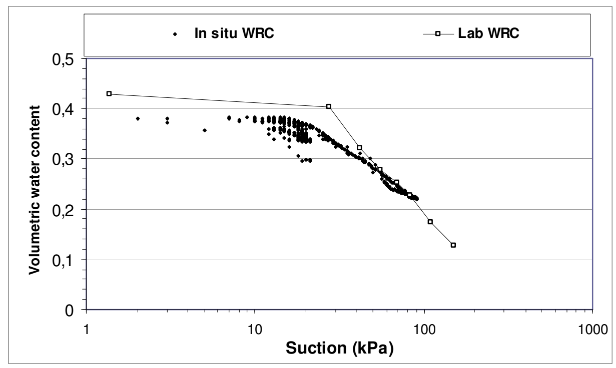


Figure 11: Comparison between laboratory and *in situ* water retention curves of the MRN tailings used in the moisture-retaining layer.

To better asses the presence of hysteresis effects, a series of data corresponding to a drying spell (a period without precipitations) and another series where precipitation events occurred (wetting phase) were compared in Figure 12.

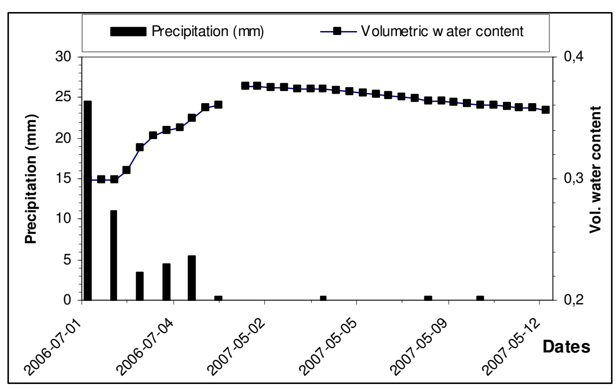


Figure 12: Evolution of water content and precipitation during drying and wetting period

The corresponding results in the $\theta$-$\psi$ plane are presented in Figure 13, where the difference between the wetting and drying processes is observed. This Figure shows that for suction between about 10 and 25 kPa, the difference in the volumetric water content could be as high as 0.07 depending on the process involved (higher values for the drying phase). Such results could have an important impact when estimating the efficiency of the cover.

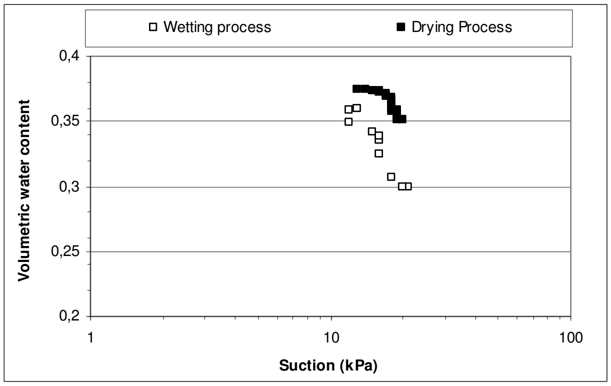


Figure 13: *In situ* water retention curve of the MRN during wetting and drying process

## 5 CONCLUSION

Regular daily measurements of the volumetric water content and suction are used in this study to better understand the transient hydrogeological behaviour of an existing CCBE. The main results are:

- The volumetric water content values in the moisture-retaining layer is higher than those measured in capillary break layer; the contrast between these values confirms the presence of the capillary barrier effect in the LTA cover.
- For both stations (CS 06-10 and PS 06-25), the volumetric water content near the base of the moisture-retaining layer is higher than near the top of the layer.
- Wetting of the cover is directly related to precipitation events. The importance of the volumetric water content increase in the moisture-retention layer varies with the intensity and duration of precipitation.
- Fluctuations of the $\theta$ values in the capillary break layer are less notable than in the moisture-retaining layer; however these fluctuations are more pronounced in the sloping area than on the flat surface. This effect is attributed to the location of the zone (known as the DDL) where the water starts to infiltrate the bottom capillary break layer.
- During the winter period, a significant decrease in the volumetric water content was observed in the moisture-retaining layer for the flat area; the decrease in $\theta$ is larger near the top of the moisture retaining layer than at its base. This behaviour is related to the freezing which reduces the amount of unfrozen water volume in the moisture-retaining layer.
- The $\psi$ measurements are in accordance with the volumetric water contents values. The difference between $\psi$ measurements near the top and the base of the moisture-retaining layer are mainly attributed to the difference in elevation of the Watermark probes.
- Hysteresis effects are identified from the *in situ* water retention curve where one can observe a net difference between the wetting and drying phases.

The results presented here are being analyzed further so additional results will be presented elsewhere.

## 6 ACKNOWLEDGMENTS

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